Predicting and Avoiding Die Attach, Wire Bond, and Solder Joint Failures

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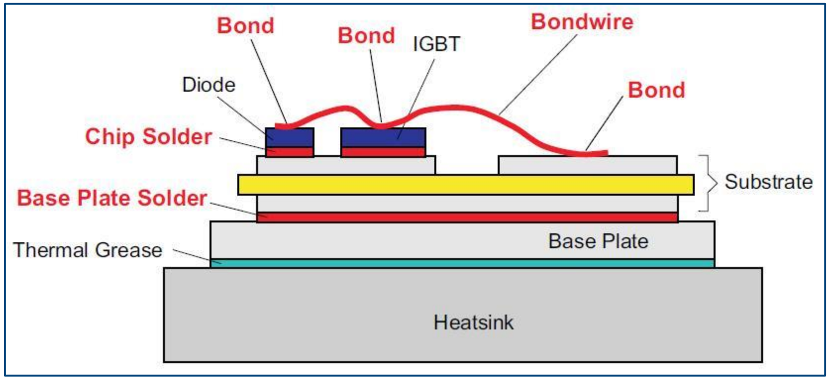
Why Die Attach/Wire Bonds/Solder Joints?

- Interconnects tend to be the primary driver for reliability of power modules
  - Influenced by the robustness of today's power devices (IGBT and FET, Si/GaN/SiC) and the tendency to towards conservative design (derating margin)



Active endurance tests of direct-bonded-copper based MOSFET power modules showed that <u>the aluminum bonds</u> and <u>the die attach</u> are the most critical design elements regarding product reliability – Robert Bosch, 2016

How to Avoid Die Attach, Wire Bond Failures?

- Step 1: Good quality control
- Step 2: Perform reliability prediction using physics of failure (PoF)

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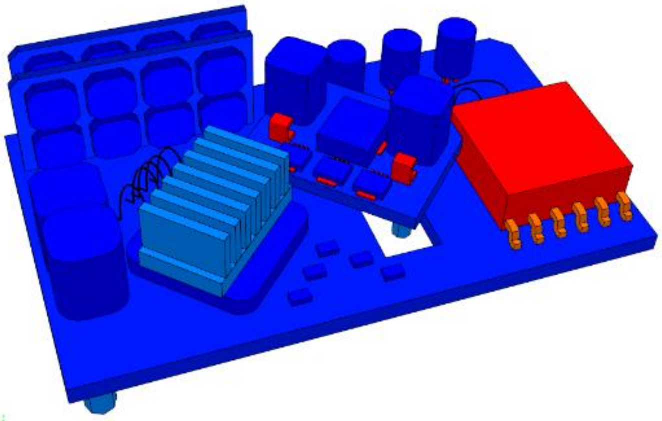
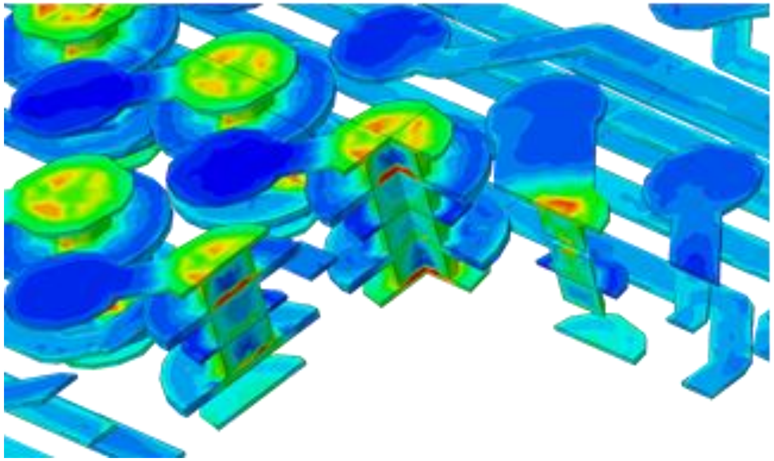
What is Physics of Failure (PoF)?

- Also known as reliability physics

- <u>Common Definition</u>:
  - The process of using modeling and simulation based on the fundamentals of physical science (physics, chemistry, material science, mechanics, etc.) to predict reliability and prevent failures





Physics of Failure: Modeling and Simulation

- What are we modeling / simulating?
- Reliability (t > 0) = Material Change or Material Movement
- Fundamental Material Mechanisms
  - Diffusion
  - Oxidation/Reduction
  - Creep
  - Fatigue

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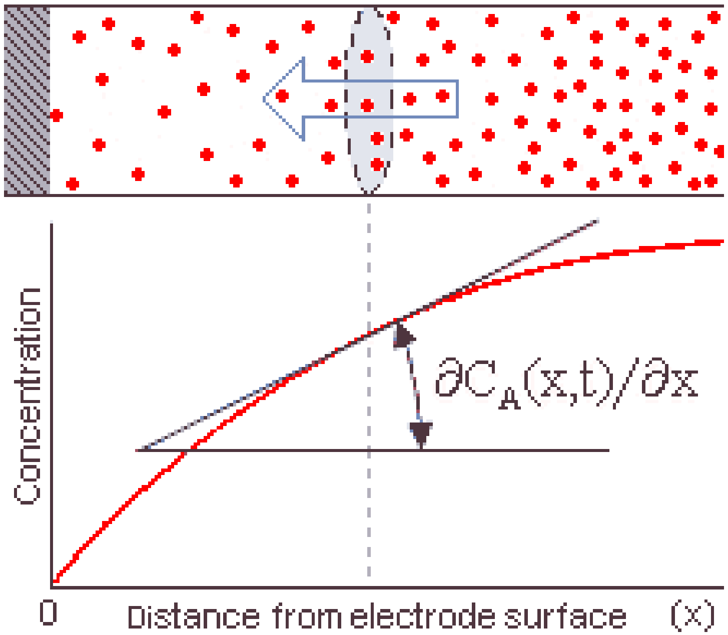
Material Movement: Diffusion

- Motion of electrons, atoms, ions, or vacancies through a material
  - Typically driven by a concentration gradient (Fick's Law)



$$J_A(x,t) = -D_A \frac{\partial C_A(x,t)}{\partial x}$$

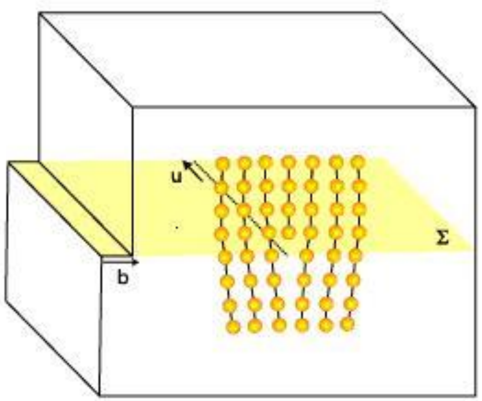
$$n(x,t) = n(0)\left[1 - 2\left(\frac{x}{2\sqrt{Dt\pi}}\right)\right]$$

  - Can be driven by other forces (electromotive force, stress)

Material Movement: Creep

- The tendency of a solid to permanently deform when subjected to a fixed load
  - Corollary: Tendency of a solid to relieve stress when loaded at a fixed displacement

- Metals: Driven by movement of defects within the crystalline structure
  - Dislocations (edge or screw)
  - Grain Boundaries



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Material Movement and M&S

- All physics of failure models can be condensed into answers to three questions
  - How large is the stress?
  - At what rate is this stress driving material movement?
  - At what time will this material movement induce failure?

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PoF-Based Reliability Prediction

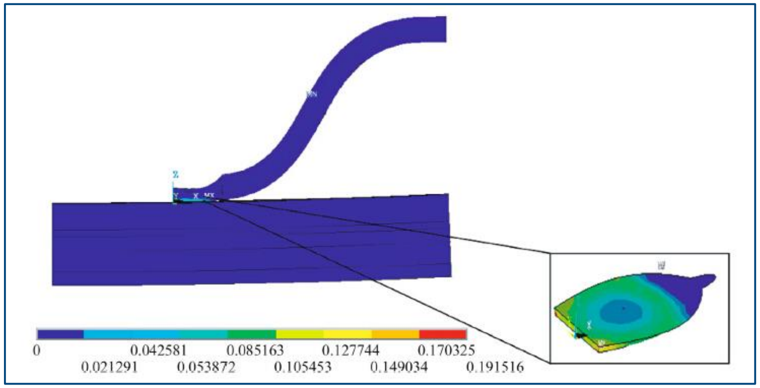
- Most physics-of-failure (PoF) based models are semi-empirical
  - The basic concept is still valid
  - Requires calibration

- Calibration testing should be performed over several orders of magnitudes
  - Allows for the derivation of semi-empirical constants, if necessary

- The purpose of PoF is to limit, but not eliminate, the influence of material and geometric parameters
  - E.g., Solder: Testing must be re-performed for each package family (ball array devices, gullwing, leadless, etc.)

How to Perform PoF? Stress/Strain/Energy

- One of the key differentiations in PoF techniques is how to capture the stress/strain/energy within the interconnect



$$\varepsilon = 6\left(\frac{r}{D}\right)\left(\frac{L}{D}-1\right)^{0.5}\left[2\alpha_{base} + \frac{\alpha_{base}-\alpha_{wire}}{1-\left(D/L\right)}\right]\Delta T$$

Option 2: Analytical Equations

Option 1: Finite element model

- Most manufacturers will use Option 1 at some point during the development process (especially for complex geometries)
  - However, Option 2 is preferred for tradeoff analysis and for users of the power modules

How to Perform PoF? Damage Accumulation

- Lots of discussion about key damage parameter (stress, strain, elastic, plastic, plasticity, creep, energy)

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f'}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c$$

Basquin
(high-cycle)

Coffin-Manson
(low-cycle)

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C\Delta K^m$$

Paris
(high-cycle)

$$N_0 = C_1 \times (\Delta W_a ve)^{C_2}$$

$$\frac{da}{dN} = C_3 \times (\Delta W_{ave})^{C_4}$$

Darveaux
(low-cycle)

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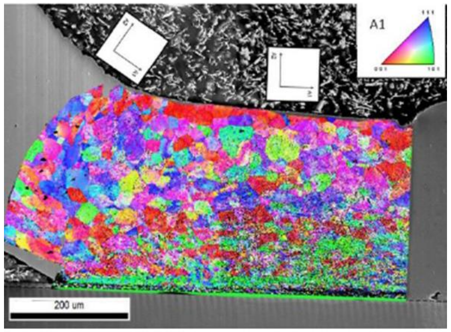
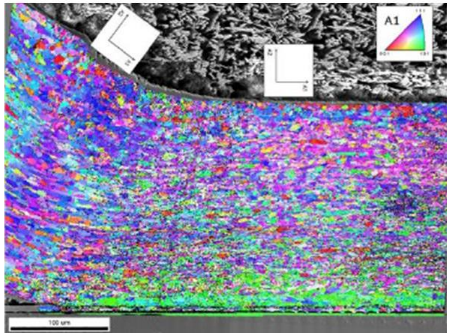
How to Perform PoF? What's Important?

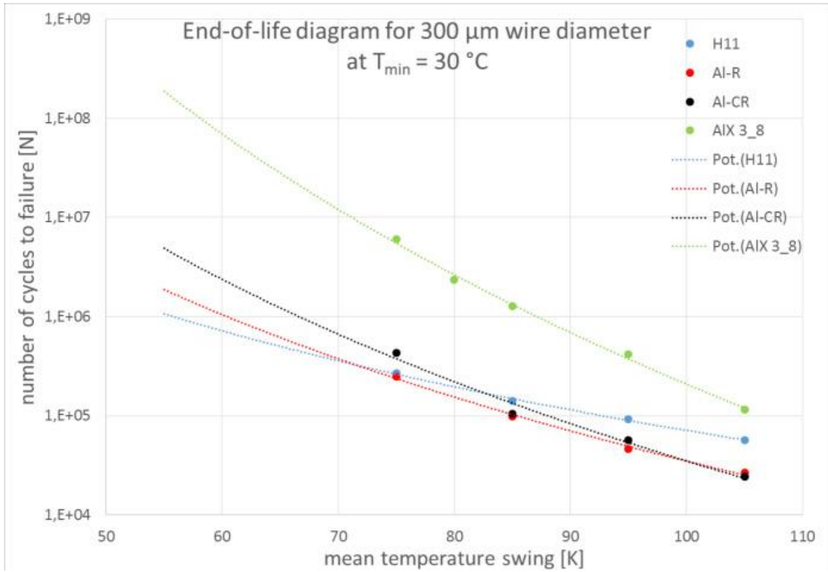
- One of the most critical aspects of PoF is including primary parameters and excluding secondary effects
  - Can sometimes drive the semi-empirical nature of PoF

b) Al-R



c) Al-CR





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Predicting Reliability of Die Attach

Predicting the Reliability of Die Attach

- Die attach tends to have only one failure mode
  - Thermal cycle fatigue due to power cycling
- Frequency of the power cycle can play a very critical role
  - If the power cycle frequency is high enough, the failure site will shift from the die attach to the wire bond (thermal inertia)
- Key Challenge: Defining failure
  - Most die attach configurations do not conduct electricity
  - Die attach is primarily a thermal path

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Die Attach Fatigue (Englemaier, 1982)

$$\Delta\gamma = \frac{(\sqrt{L_d^{\ 2} + W_d^{\ 2}})(CTE_{die} - CTE_{DBC})\Delta T}{2h}$$

Strain range at the die/die attach interface

- h = die thickness
- W = die width
- L = die length

- α = coefficient of thermal expansion (CTE)
- ΔT = change in temperature

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Die Attach Fatigue (Time to Failure)

$$N_f = \varepsilon_f (\Delta\gamma)^c$$

- Coffin-Mason based low-cycle fatigue damage model
- Tin-based solders (SnPb, SAC305, Sn3.5Ag, etc.) tend to have fatigue exponents around 2 to 2.5
  - SnPb: ~2; Sn3.5Ag: 2.2; SAC305: ~2.4
- Fatigue exponents for new die attach solders have not yet been widely validated
  - Nanosilver, BiAgX, Sn25Ag10Sb ("J" alloy)

Nanosilver: Is it Better Than Solder?

- Sintering with nanosilver is challenging (and expensive)
  - Requires pressure
  - For large die, post sintering stress relief step is often required
  - Voiding must be controlled

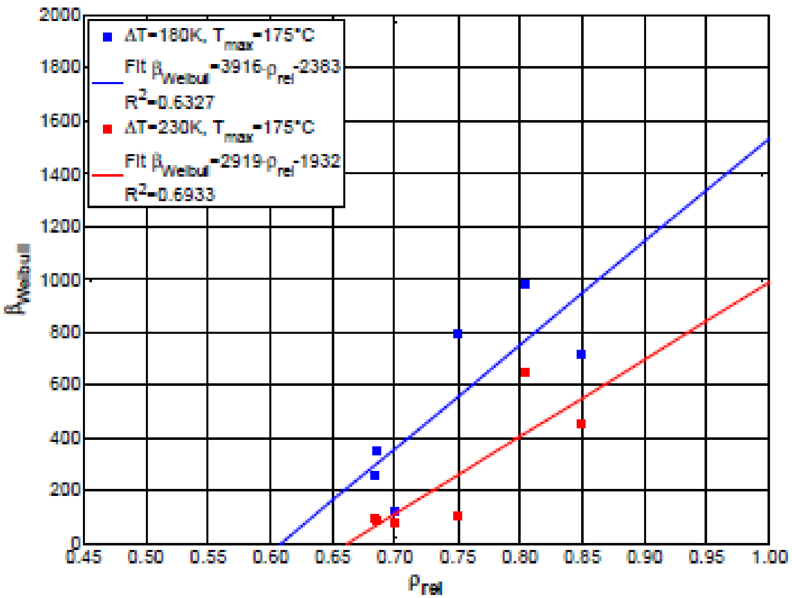
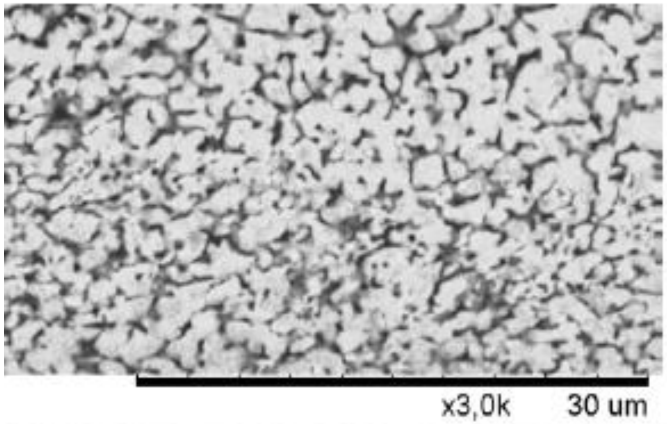
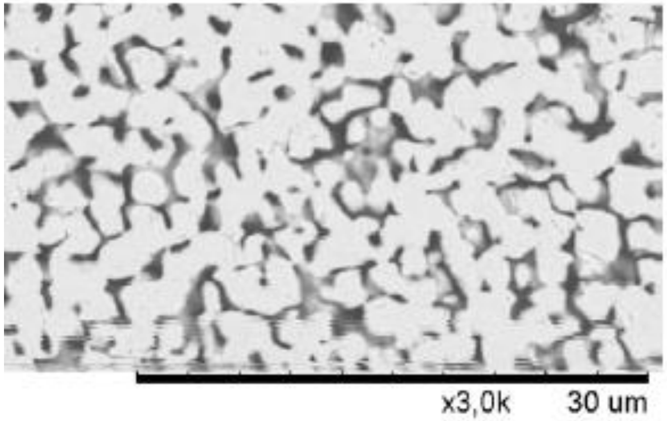


Fig. 8 Plot of characteristic lifetime of sintered joints during thermal cycling vs. density.





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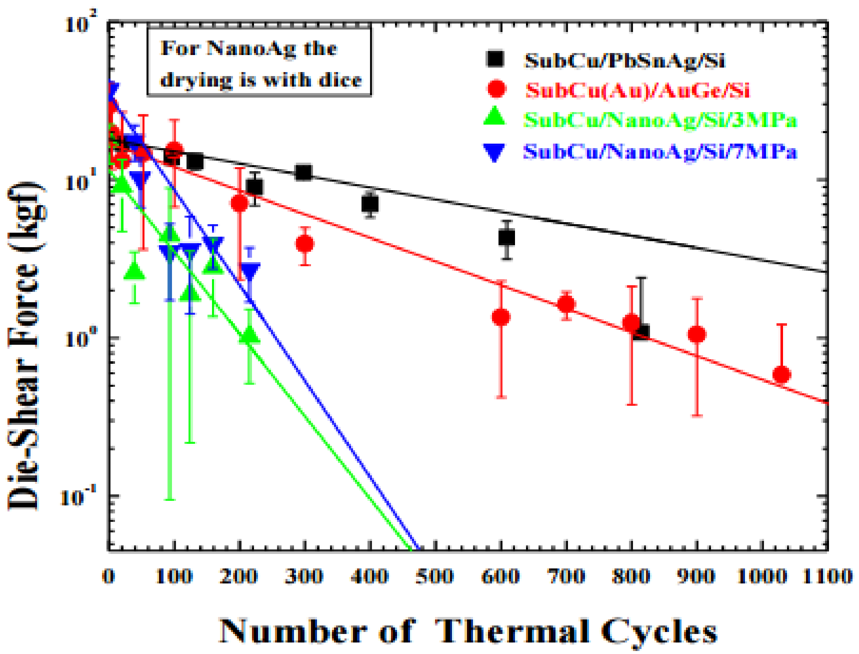
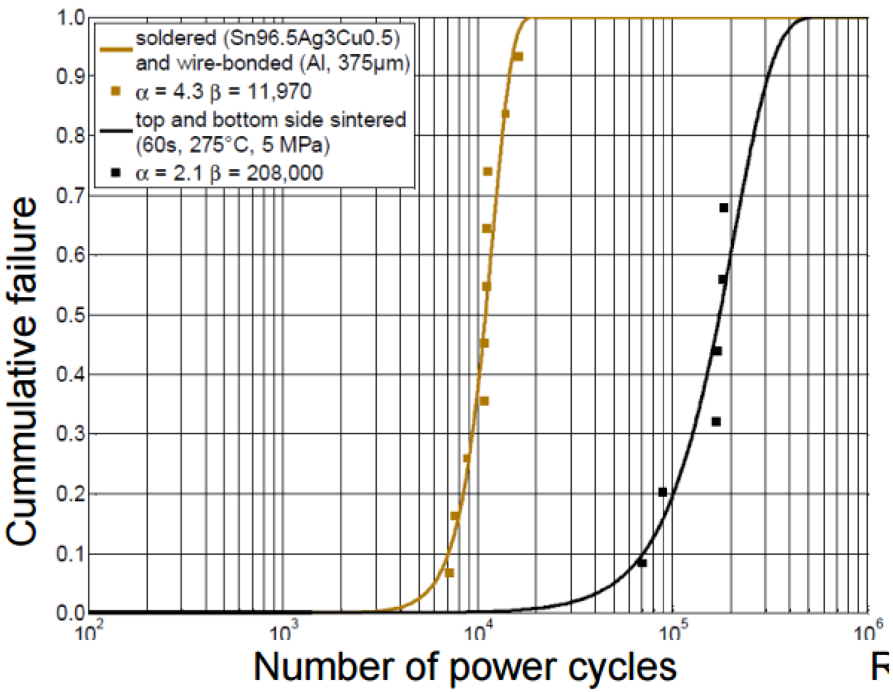
Nanosilver: Is it Better Than Solder? (cont.)

- For the most part, the industry agrees nanosilver is more reliable, but there can be issues



L. Melchor, Doctoral Dissertation



M. Beierlein, Adv. Pack. Conf. 2013

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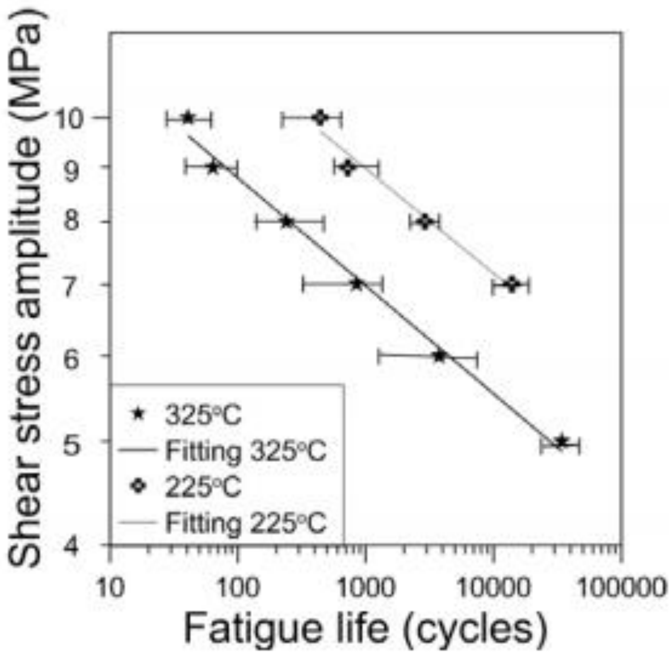
Nanosilver: Is it Better Than Solder? (cont.)

- Different publications provide different values for fatigue constants and exponents

$$N_{f,\mathrm{Sn96{,}5Ag3Cu0{,}5}} = 0{,}075 \cdot \Delta\varepsilon_{\mathrm{plastic}}^{-1{,}79}$$

$$N_{f,\mathrm{Nano\text{-}Silver}} = 0{,}160 \cdot \Delta\varepsilon_{\mathrm{plastic}}^{-2{,}96}$$

Author	Constant	Value	Exponent
M. Knoerr	1.6E-01	Plastic Strain	-3.0
Y. Tan	5.8E+11	Shear Stress	-9.4
X. Li	1.6E-09	Shear Strain	-7.6



Y. Tan, et. al., Conf. on Fracture, 2013

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Vibration Fatigue

- Lifetime under mechanical cycling is divided into two regimes
  - Low cycle fatigue (LCF)
  - High cycle fatigue (HCF)
- LCF is driven by inelastic strain (Coffin-Manson)

$$\varepsilon_p = \varepsilon_f \left(2N_f\right)^c$$

-0.5 < c < -0.7; 1.4 < -1/c > 2

- HCF is driven by elastic strain (Basquin)

$$\varepsilon_e = \frac{\sigma_f}{E}\left(2N_f\right)^b$$

-0.05 < b < -0.12; 8 > -1/b > 20

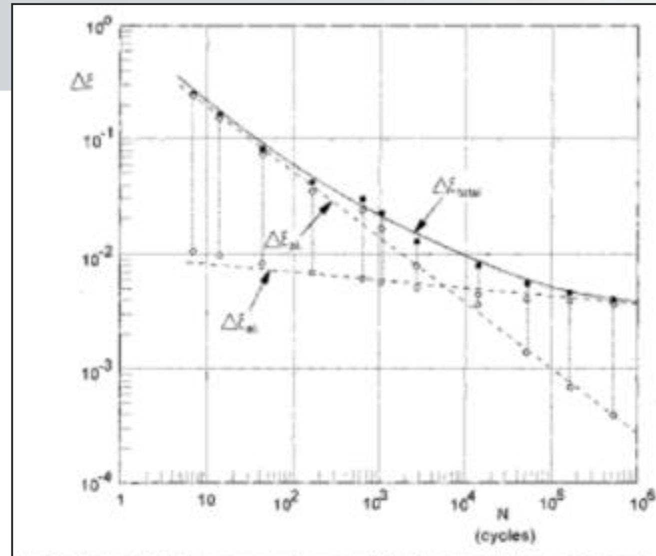
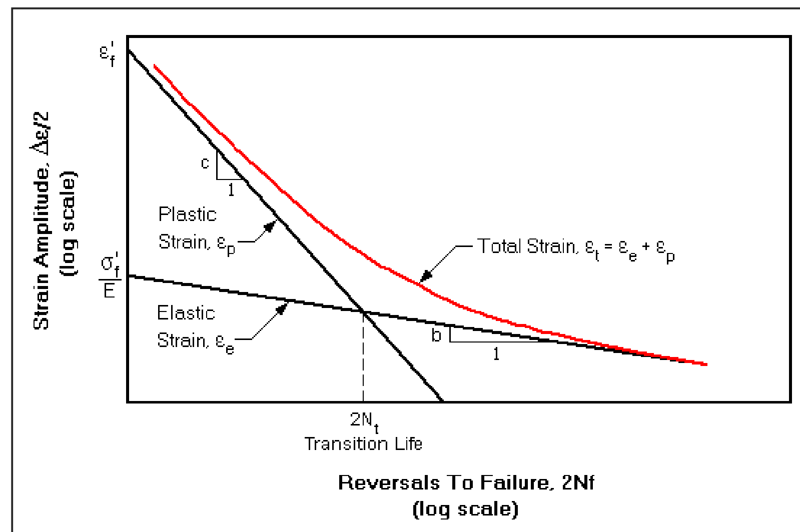


Fig.6.19: Total strain range as the sum of the plastic and the elastic strain range. Material: AISI 4340 (annealed) [19]. (Range $\Delta\epsilon = 2\cdot\epsilon_a$).



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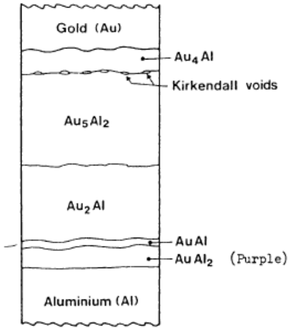
Predicting Reliability of Wire Bonds

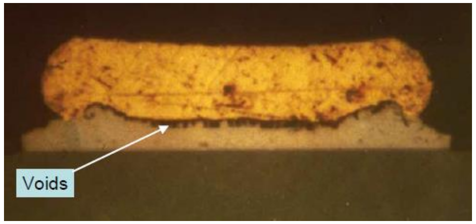
Reliability: When do Wire Bonds Fail?

- Exposure to elevated temperature
  - Intermetallic formation
- Exposure to elevated temperature/humidity
  - Corrosion
- Exposure to temperature cycling
  - Low cycle fatigue

Reliability at Elevated Temperatures

- Not an issue in aluminum-aluminum wire bond system
  - The lack of intermetallic formation and differential diffusion makes it relatively immune to purple plague
  - Prior studies have found little change in resistance after 1000 hours at 300C
- Bigger issue in mixed metal systems, like gold-aluminum
  - Formation of brittle AuAl2 (purple plague) at 350C
  - Diffusion of gold into Au_5Al_2 causes Kirkendall voiding at lower temps





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Reliability Prediction (Elevated Temperature)

- Is an absolute reliability prediction of wire bond reliability at elevated temperature possible?
- Short answer: NO
  - Diffusion behavior is very sensitive to bonding temperature, quality of bond, aluminum alloy, aluminum bond pad thickness, and encapsulant chemistry
    - Low bonding temperature
    - Si in Al-Cu bond pad
    - Thin bond pad (~1 um)
    - Bromide-free flame retardants
  - Can change absolute and relative (acceleration factor) time to failure

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Reliability Prediction – Temperature (cont.)

- For gold-aluminum, prediction is primarily by extrapolation from test results using Arrhenius and a conservative activation energy (0.9 eV)

$$t_f = A\exp\left(\frac{\Delta H}{kT}\right)$$

- However, there is some question as to the presence of a minimum temperature
  - Periodically reported as 125C for unencapsulated and 85C for encapsulated
  - Observed in other systems (tin-copper and whiskers)

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Other Systems (Cu-Al)

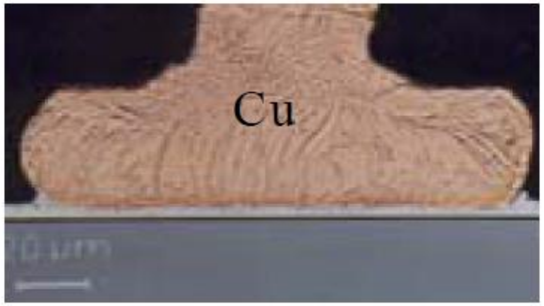
- Copper-aluminum forms intermetallics at a much slower rate

HJ Kim, IEEE CPT, 2003

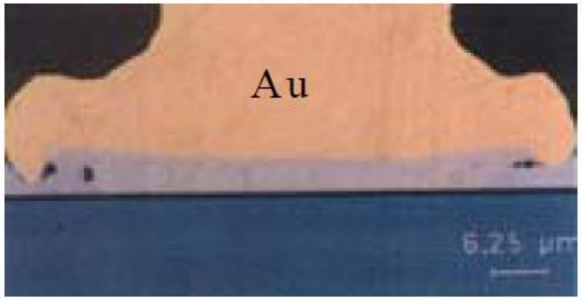
  - Most common activation energy of 1.26 – 1.47 eV
    - Micron reported 0.63 eV

L. England, ECTC, 2007

- Molding compound has little effect

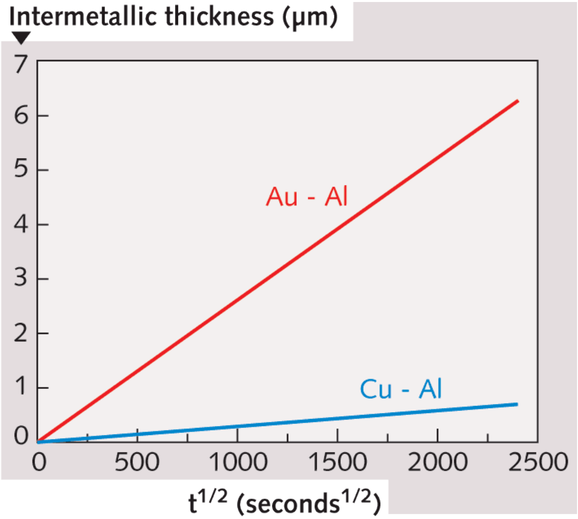


Intermetallic Penetration - AlSi-Cu Bond
(aged 800 hours at 180°C)



Intermetallic Penetration - AlSi-Au Bond
(aged 200 hours at 200°C)

L Levine, Update on
High Volume Copper Ball Bonding



C. Breach, The Great Debate: Copper vs. Gold Ball Bonding

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Other Systems (Cu-Al)(cont.)

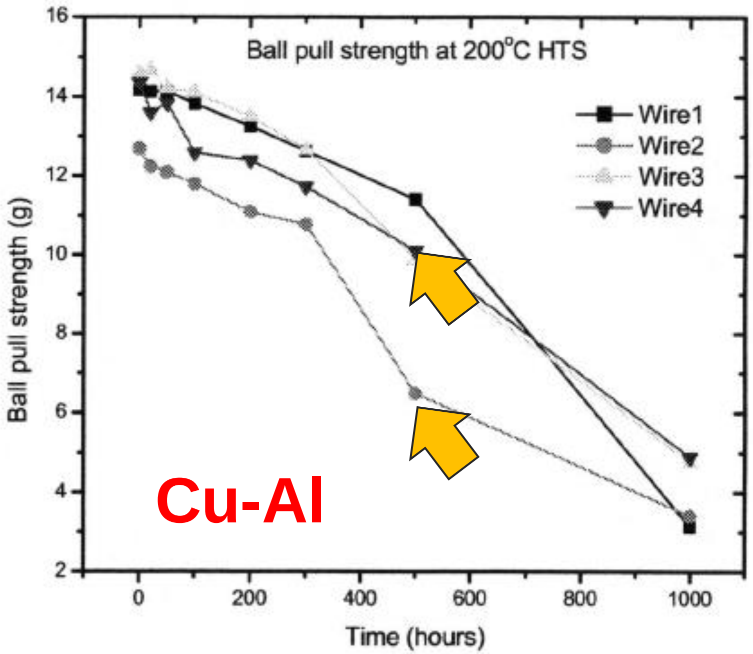
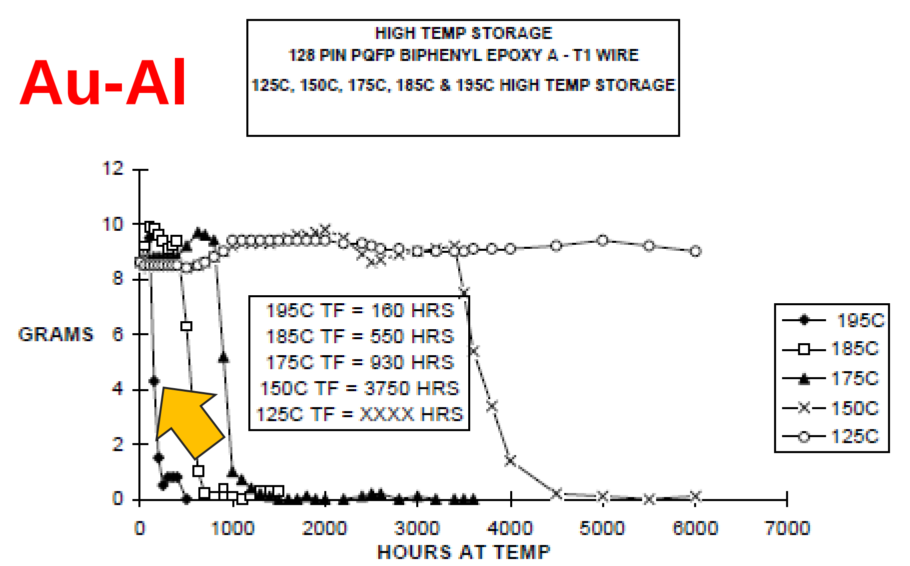


Figure 6. Ball Pull Strength after HTS at 200°C



- Cu-Al can show improved performance over Au-Al
  - Not to the extent expected based on intermetallic growth
  - Different failure mode (gradual vs. sudden)

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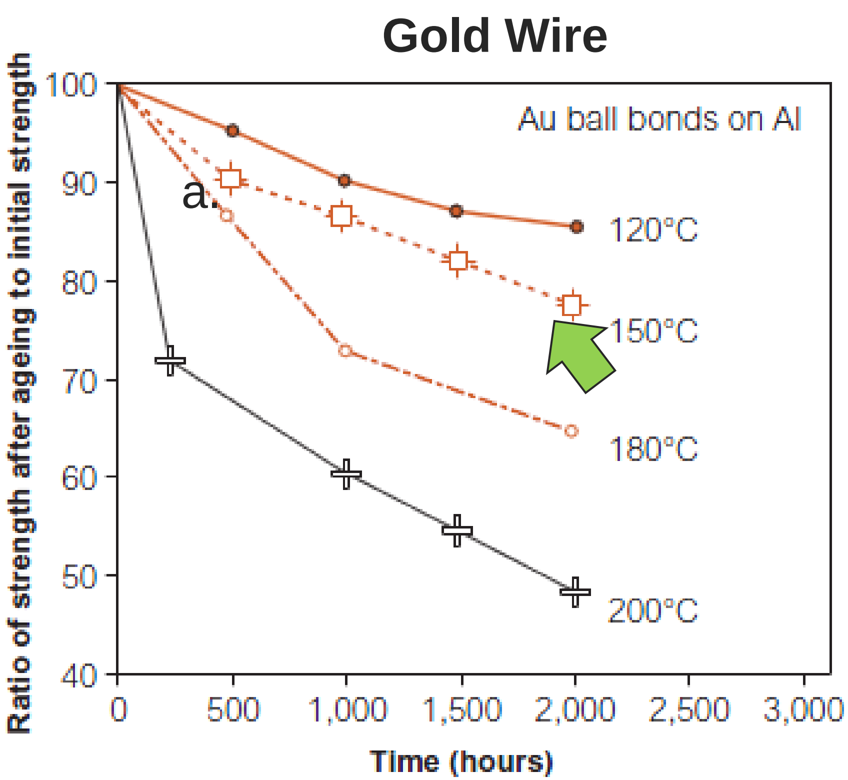
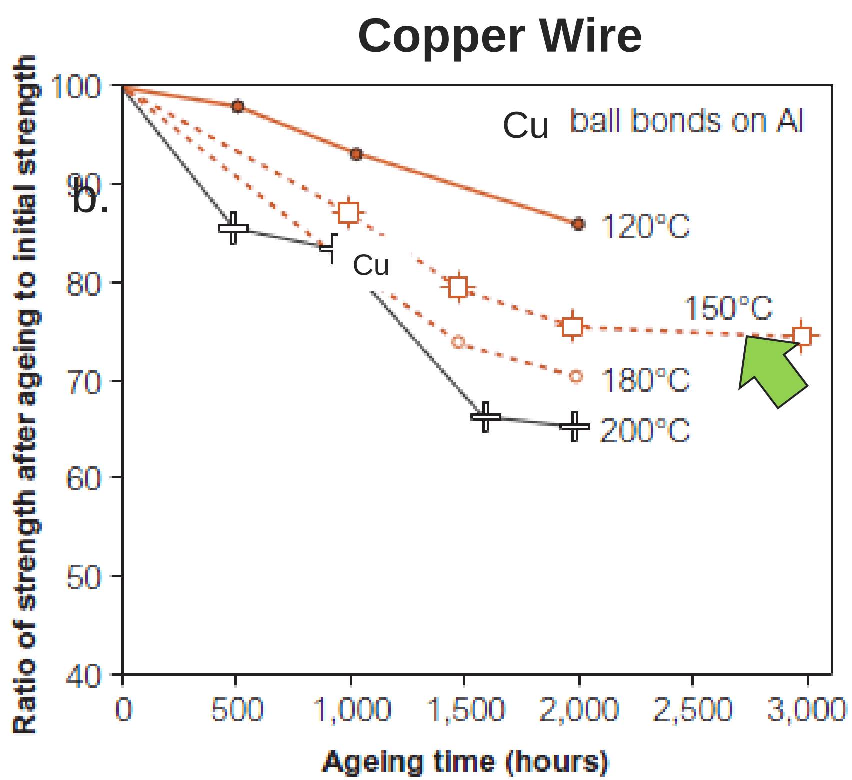
Shear Strength at Elev Temp



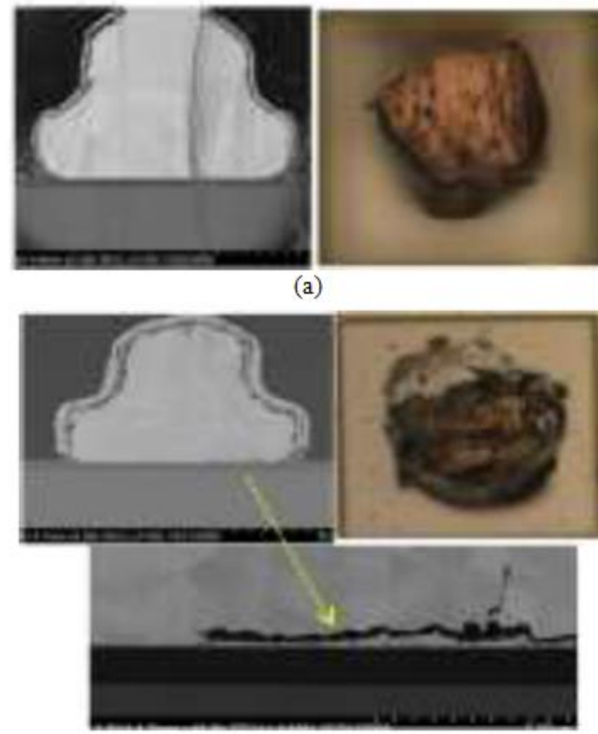


- Shear strength of Au and Cu ball bonds on Al pads
- At lower temperatures (<150C) they are similar in strength loss

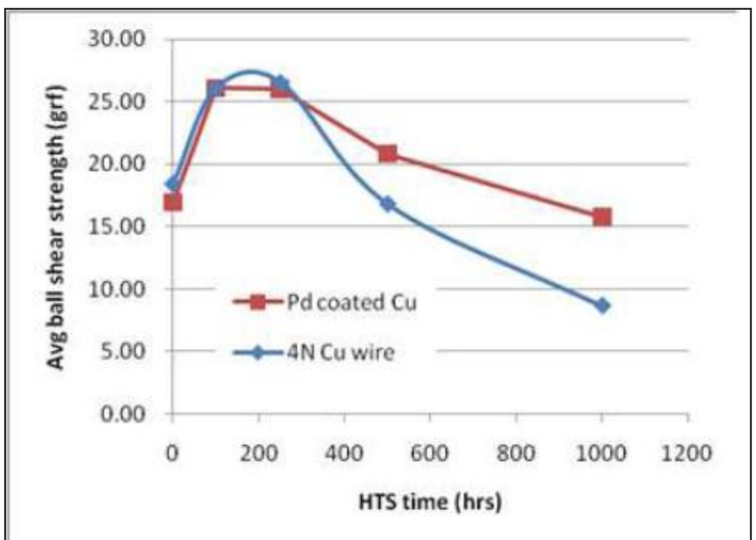
J. Onuki, M. Koizumi, I. Araki. IEEE Trans. On Comp. Hybrids & Manfg. Tech. **12** (1987) 550

Cu-Al and Elevated Temperature – Concerns

- Different intermetallics form at different temperatures
  - Can a 150C/200C test be extrapolated to 85C?
  - Fracture mode with pure Cu changed from bulk Cu to interfacial failure



- Some indications that oxidation of the wedge bond may be a critical weak point



S. Na, T. Hwang, J. Kim, H. Yoo, and C. Lee, "Characterization of IMC growth in Cu wire ball bonding on Al pad metallization", ECTC, IEEE, 2011

Wire Bonds and Temperature/Humidity

- Degradation primarily occurs in the gold wire bond / aluminum bond pad system
- Driven by galvanic corrosion
  - Absence of galvanic couple in aluminum/aluminum and copper/aluminum systems tends to limit corrosive behavior
- Presence of halides, especially chloride, can accelerate corrosive behavior
  - Getters in the molding compound tend to reduce this risk

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Wire Bonds and Temperature/Humidity (cont.)

- The mechanism of Au-Al corrosion has been primarily described by Peck's Law
- Peck's Law for Temperature and Humidity
  - Empirical study of THB/HAST (85/85, 110/85 & 5-70 VDC)

$$t_{life} = A_0 RH^{-n} f(v) \exp\left(-E_a/kT\right)$$

t_{life} = time to failure,

RH = relative humidity,

E_a = activation energy (0.79eV),

T = temperature,

A_0 = material constant

n = empirical constant (2.66)

k = Boltzmann constant

$f(v)$ = voltage function (power law, ~1.5)

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Copper Wire Bond and Temperature/Humidity

- Copper is not as noble as gold
  - Noble coatings (palladium) can come off during bonding
  - Palladium (Pd) coating can also create galvanic couple with copper
- Studies have shown early failures during temp/humidity testing
  - Some dependency on molding compound (need lower pH, lower halogen content)
  - Uncertain if JEDEC test with acceleration factor based on Peck's equation (based on aluminum/gold) is still valid

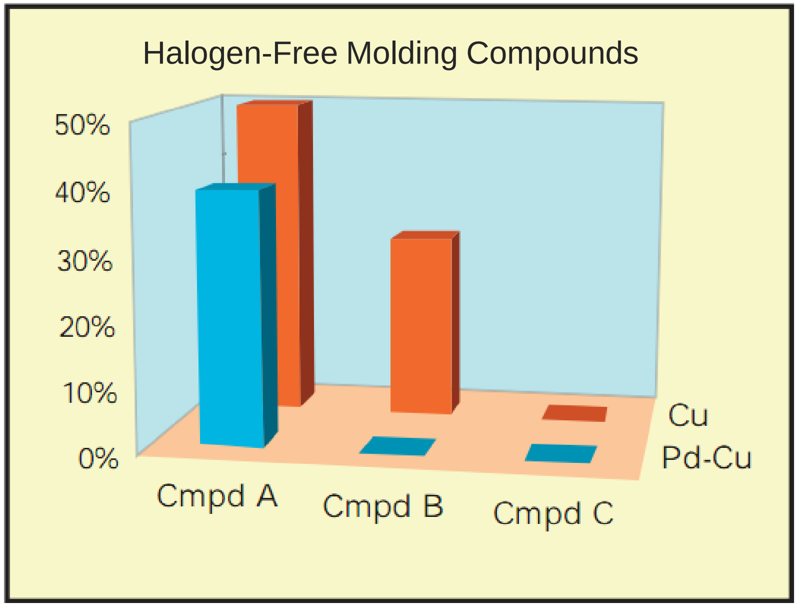

Figure 6. Failure rates after 336 hours biased HAST test for three experimental mold compound formulations with 0.8 mil bare Cu and Pd-coated Cu wire on Al bond pads. (5V bias, 130oC, 85% RH, electrical open/short

H. Clauberg, Chip Scale Review, Dec 2010

Copper Wire Bond and Temperature/Humidity (cont.)

- T. Boettcher believe early failures are due to galvanic corrosion of Cu-rich intermetallics (Cu_9Al_4) (EPTC 2010)
  - Induces the formation of copper oxides between the intermetallic and the copper bond wire

- Initial failures during JEDEC HTRB and Autoclave testing were reversed by increasing the amount of intermetallic through annealing
  - Small anode (intermetallic) relative to cathode greatly increases corrosion rate

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Status of Cu-WB Durability-Reliability Research iNEMI P2B

- iNEMI Phase 2B: HAST 130degC/85% Rel. Humidity for 384 hours on loose parts
  - Tested every 4 days at 96, 192, 288 and 384 hours.
  - Failure pattern suggests more of a durability issue (however, how relevant is 384 hours under HAST?)

Fig14. HAST 130degC/85%RH Test Result for BGA

	96hrs	192hrs	288hrs	384hrs
BGA1	0/24	0/24	0/24	0/24
BGA2	0/34	0/34	1/34	1/33
BGA3	1/34	0/33	0/33	1/33
BGA4	0/34	0/34	0/34	2/34
BGA5	0/34	0/34	0/34	1/34
BGA7	0/96	0/96	0/96	0/96

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Wire Bonds and Temperature Cycling (Wedge Flexure)

- Driven by differences in coefficient of thermal expansion (CTE)
  - Flexing motion results create microcracks at the heel of the wirebond
  - Model based on theory of curved beams

$$\varepsilon = 6\left(\frac{r}{D}\right)\left(\frac{L}{D}-1\right)^{0.5}\left[2\alpha_{base} + \frac{\alpha_{base}-\alpha_{wire}}{1-(D/L)}\right]\Delta T$$

Strain at the heel of the wire
(assumes bond pads at same height)

- r = wire radius
- D = half wire span
- L = wire length
- α = coefficient of thermal expansion (CTE)
- ΔT = change in temperature

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Wedge Flexure (cont.)

- Coffin-Mason Based Low-Cycle Fatigue

$$N_f = C\varepsilon^m$$

- **C** and **m** empirically determined to be 1.0 and (-1.4) respectively for aluminum wedge bonds

Wire Bonds and Temperature Cycling (Axial Tension)

- Wire encapsulated in molding compound can experience tensile stresses in the wire due to differential expansion and contraction

$$\sigma_w = E_w(\alpha_e - \alpha_w)\Delta T$$

Modulus of molding compound is ignored because of its minimal contribution

$$N_f = C\sigma^m$$

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Wire Bonds and Temperature Cycling (Shear)

- Shear stresses between the substrate (s), the bond pad (p) and the wire (w)

$$\tau_{w,M} = \left\{ \frac{r^2}{4Z^2A_w^2} \left[\frac{\cosh(Zx_w)}{\cosh(Zl_w)} - 1 \right]^2 + \frac{\sinh^2(Zx_w)}{\cosh^2(Zl_w)Q^2} \right\}^{1/2} \Delta T$$

- r is wire radius
- A is cross-sectional area
- W is width
- G is shear modulus
- b is thickness
- l is length

$$Z^2 = \frac{G_p}{b_p}\left[\frac{r}{E_w A_w} + \frac{(1-\nu_s)W_p}{E_s A_s} \right]$$

$$Q = \frac{G_p}{b_p Z}\left[(\alpha_w - \alpha_s) + \frac{(\alpha_s - \alpha_p)}{1 + (E_s A_s)/[E_p A_p (1-\nu_s)]} \right]$$

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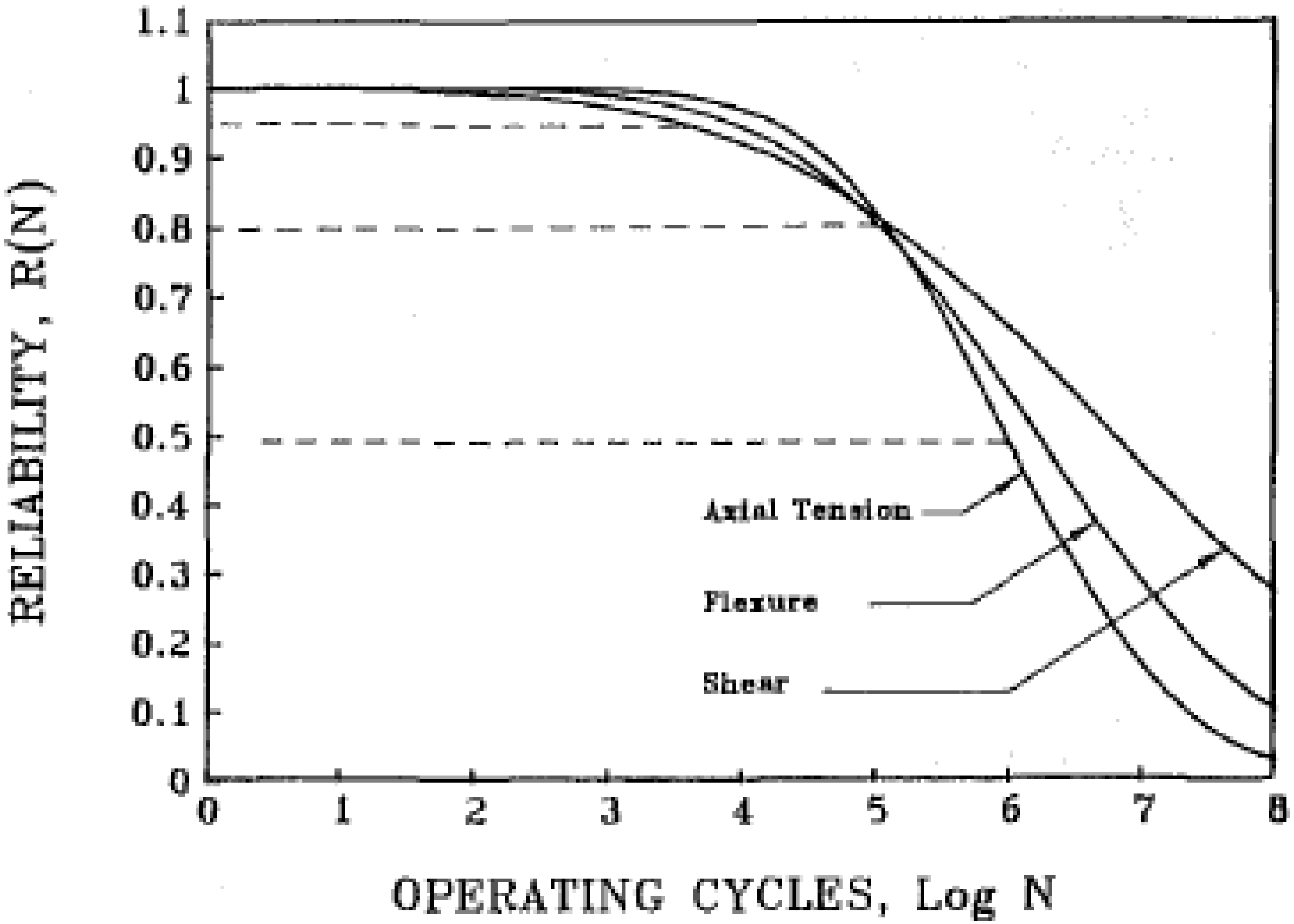
Competing Failure Mechanisms



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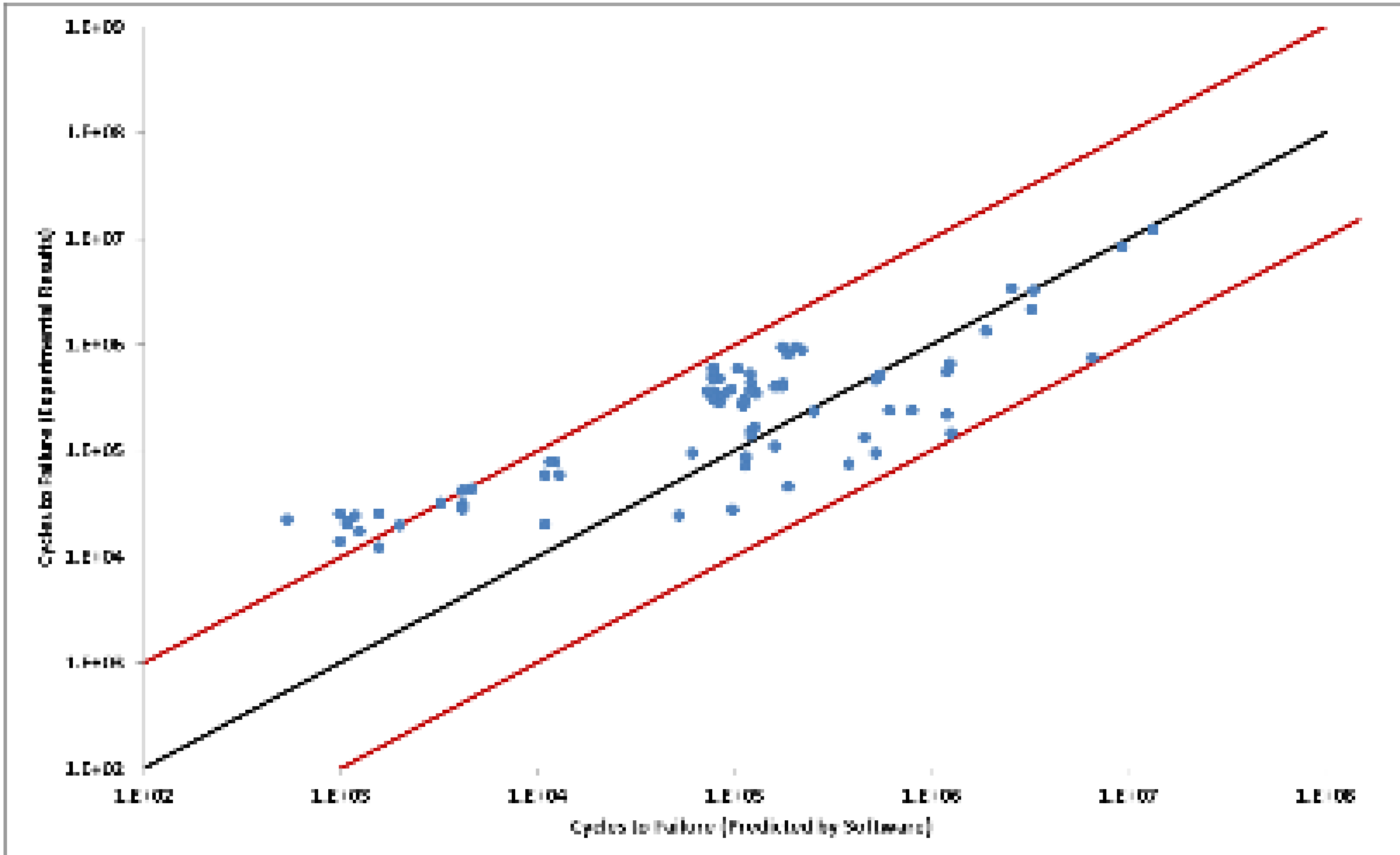
Validation (Aluminum-Aluminum System)



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Copper Wire and Temperature Cycling

- Power module industry believes copper wire is more robust than aluminum
  - Changes being implemented for electric drivetrain
- Part of improvement is believed to be due to reduced temperature variation from improved thermal conductivity
- Part of improvement could be due to recrystallization N. Tanabe, Journal de Physique IV, 1995
  - Can result in self-healing
- Part of improvement could be more robust fatigue behavior

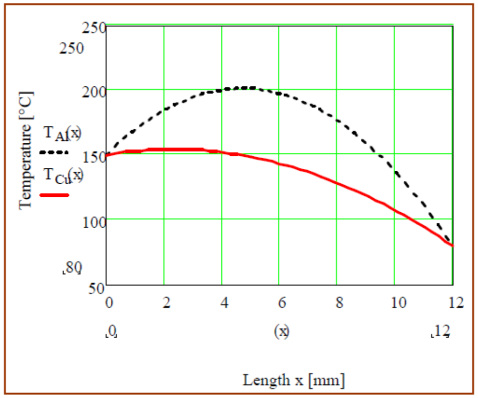


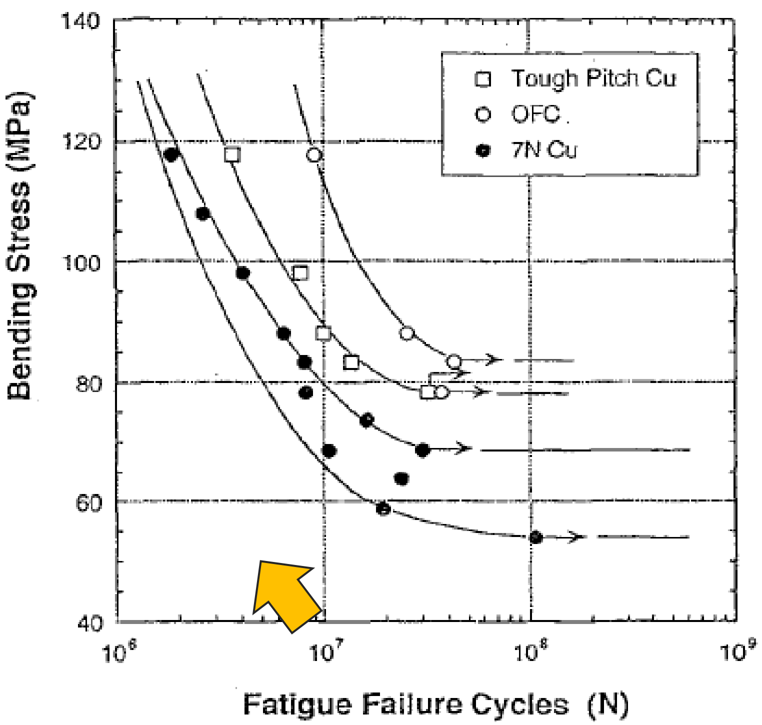
Figure 5: Temperature distribution along a 400µm wire of 12mm length, Al dashed curve, Cu solid red curve, current is 19A

D. Siepe, CIPS 2010

DfR Solutions

Copper vs. Gold – Temperature Cycling

- Copper superior based on these publications



N. Tanabe, Journal de Physique IV, 1995

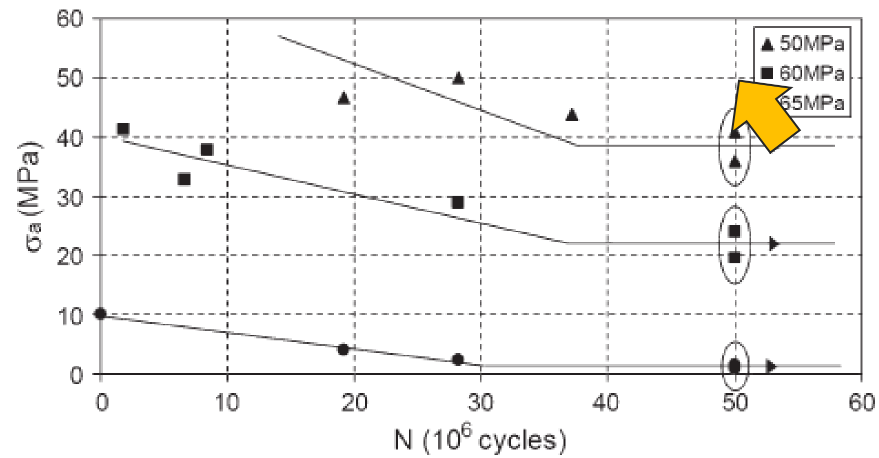
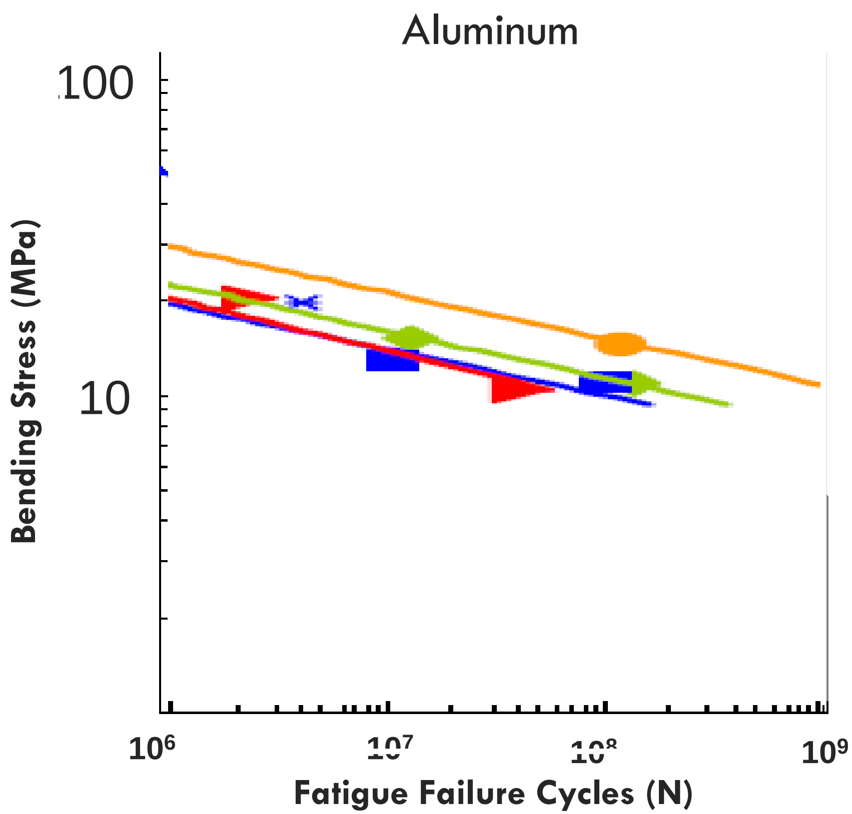


Fig. 9. Experimental results of fatigue tests in the $S-N$ diagram for three values of mean stress. Specimens marked with an arrow did not fail.

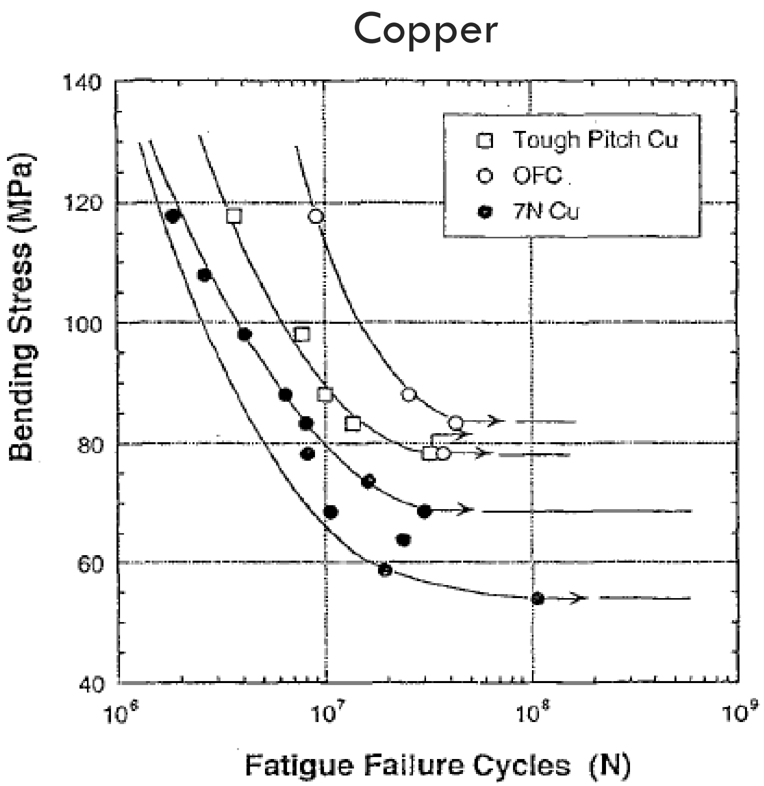
G. Pasquale, J. Microelectromech Sys.,, 2011

Aluminum vs. Copper – Temperature Cycling

- Copper seems superior



J. Bielen, EuroSime, 2006

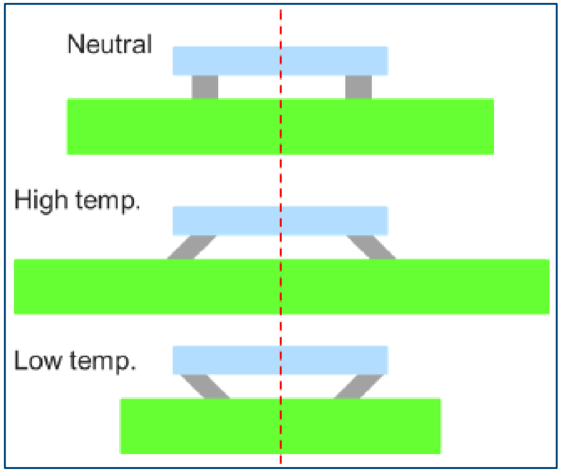


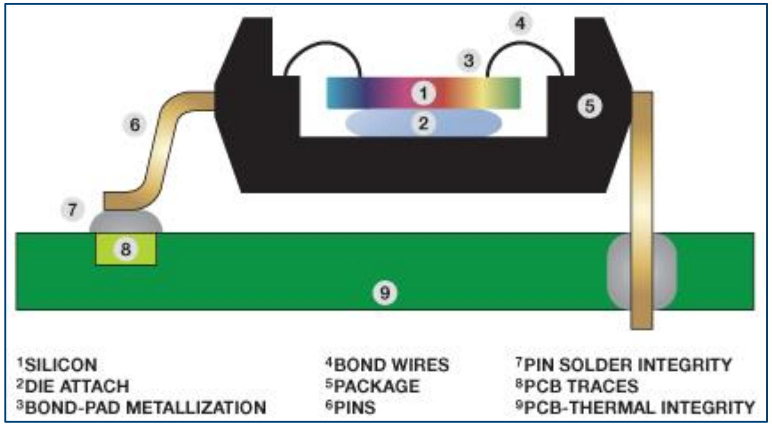
N. Tanabe, Journal de Physique IV, 1995

DfR Solutions

Thermal Cycling Reliability and Assembled Parts

- Loose Cu wire-bonded parts have passed component level thermal cycle tests, but have failed during thermal cycling of automotive E/E modules
- Believed, but not confirmed, to be due to additional expansion-contraction stresses from the CTE mismatch part and PCB



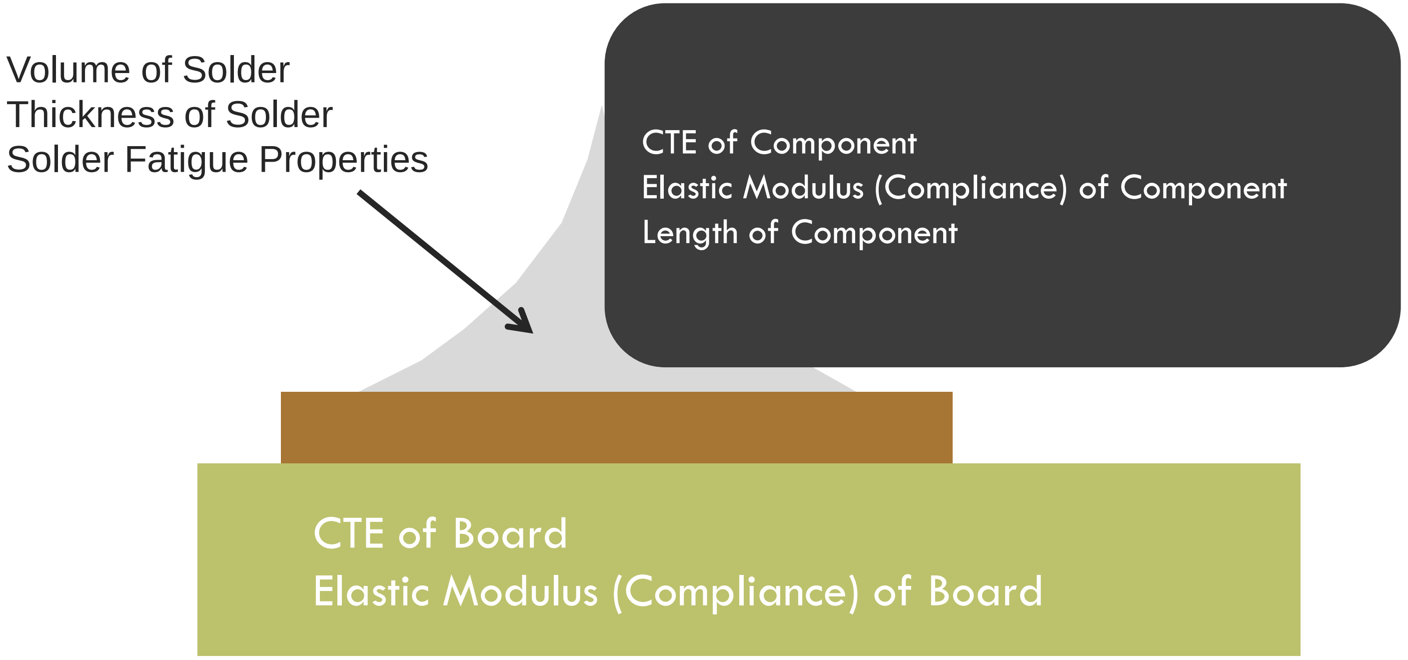


DfR Solutions

Predicting Reliability of Solder Joints

Solder Joint Fatigue

- Knowing the critical drivers for solder joint fatigue, we can develop predictive models and design rules



Predictive Models – Physics of Failure (PoF)

- Modified Engelmaier for Pb-free Solder (SAC305)
  - Semi-empirical analytical approach
  - Energy based fatigue
- Determine the strain range ($\Delta\gamma$)

$$\Delta\gamma = C \frac{L_D}{h_s} \Delta\alpha\Delta T$$

- C is a correction factor that is a function of dwell time and temperature, L_D is **diagonal distance**, α is coefficient of thermal expansion (**CTE**), ΔT is temperature cycle, h is **solder joint height**

DfR Solutions

Predictive Models – Physics of Failure (PoF)(cont.)

- Determine the shear force applied to the solder joint

$$(\alpha_2 - \alpha_1)\cdot \Delta T \cdot L = F \cdot \left(\frac{L}{E_1 A_1} + \frac{L}{E_2 A_2} + \frac{h_s}{A_s G_s} + \frac{h_c}{A_c G_c} + \left(\frac{2-\nu}{9 \cdot G_b a} \right) \right)$$

  - F is shear force, L is **length**, E is **elastic modulus**, A is the area, h is thickness, G is shear modulus, and a is edge length of bond pad
  - Subscripts: 1 is **component**, 2 is **board**, s is solder joint, c is bond pad, and b is board

- Takes into consideration foundation stiffness and both shear and axial loads

DfR Solutions

Predictive Models – Physics of Failure (PoF)(cont.)

- Determine the strain energy dissipated by the solder joint

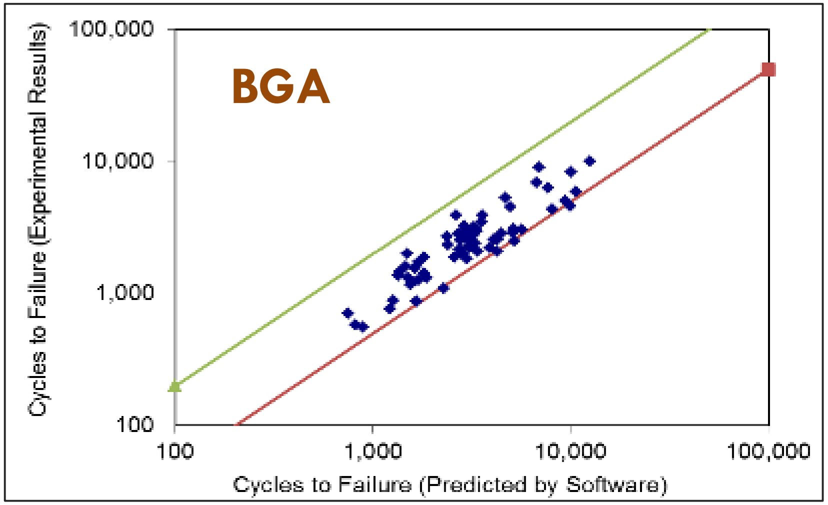
$$\Delta W = 0.5 \cdot \Delta\gamma \cdot \frac{F}{A_s}$$

- Calculate cycles-to-failure (N_{50}), using energy based fatigue models

$$N_f = \left(0.0019 \cdot \Delta W\right)^{-1}$$

Solder Joint Validation

- Energy-based analytical equation shows strong correlation to both test and field failures



- When correlation is not observed, typically driven by the presence of an axial loading condition (constraints, potting)
  - Requires use of compatibility of displacements

$$F = \frac{\Delta T(\alpha_2 - \alpha_1)}{\left(\frac{1}{A_1E_1} + \frac{1}{A_2E_2}\right)}$$

Summary / Conclusion

- The field of reliability prediction is not stagnant
  - Driven by need for new materials, new technologies
  - Driven by demand for faster time to market (can not test everything)
  - Driven by limited resources (can not FEA everything!)

- Be aware when knowledge is sufficient, validated by a physical understanding and testing, to proceed with modeling and simulation